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JUN 16 1994

FEDERAL COMMUNICATIONS COMMISSION
OFFICE OF SECRETARY

June 16, 1994

Ms. Donna R. Searcy
Secretary
Federal Communications Commission
1919 M Street, N.W.
Washington, D.C. 20554

Re: ET Docket No. 94-32

In the Matter of
Allocation of Spectrum Below 5 GHz
Transferred from Federal Government Use

Dear Ms. Searcy:

Transmitted herewith by the Committee on Radio Frequencies, operated by the National Research Council for the National Academy of Sciences, are an original and nine (9) copies of its Comments to the Notice of Inquiry in the above-referenced proceedings. CORF respectfully requests that the Commission accept the attached late-filed Comments. The courier was unable to file comments yesterday, June 15, 1994, because no parking was available near the FCC building at 5:25 p.m. The time needed to prepare the draft, have it reviewed by the committee, and pass it through subsequent NRC review necessitated the last-minute delivery.

CORF submits that no party will be harmed by acceptance of these late-filed Comments inasmuch as they repeat arguments already made regarding interference protection of the Radio Astronomy Service in the above-referenced frequency bands.

If additional information is required concerning this matter, please communicate with this office.

Sincerely yours,

Robert L. Riemer

Robert L. Riemer
Senior Program Officer

Enclosure

cc: Members of CORF

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Before the
FEDERAL COMMUNICATIONS COMMISSION
Washington, D.C. 20554

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**COMMENTS OF THE
NATIONAL ACADEMY OF SCIENCES'
COMMITTEE ON RADIO FREQUENCIES**

The National Academy of Sciences, through the National Research Council's Committee on Radio Frequencies (hereinafter, "CORF"), hereby submits its comments in response to the Commission's Notice of Inquiry ("Notice") in the above-captioned proceeding. CORF represents the interests of the Earth Exploration-Satellite Service, the Space Research Service, the Radio Astronomy community and other users of the radio spectrum engaged in scientific research.[1] CORF submits these Comments to

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[1] Although these comments will generally refer to radio astronomy, it should be noted that the concerns of radio astronomers are generally shared by all passive radio users, such as those operating in the Earth Exploration--Satellite Service, and the Space Research Service.

encourage the Commission to enact rules placing limited restrictions on the use of the reallocated 2390-2400 MHz and 2402-2417 MHz bands, in order to protect the important planetary research conducted at the National Astronomy and Ionospheric Center at Arecibo, Puerto Rico.

I. Introduction

CORF recognizes that the reallocation of certain portions of government spectrum, as required pursuant to Title VI of the Omnibus Budget Reconciliation Act of 1993,[2] is designed to, and should, encourage the development and use of new spectrum-based technologies. Congress recognized, however, that in analyzing which frequency bands should be reallocated, that substantial degradation of existing government uses of spectrum, and costs to existing users, must be weighed against potential benefits of future uses.[3] It should be noted that in the Preliminary Spectrum

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[2] Pub. L. No. 103-66; 107 Stat. 397 (August 10, 1993) (hereinafter, the "Act").

[3] See, Sec. 6001 of the Act, adding Sec. 113(c)(1)(C) to the National Telecommunications and Information Administration Organization Act: [...the Secretary shall...] seek to avoid -- (i) serious degradation of Federal Government services and operations; (ii) excessive costs to the Federal Government and users of Federal Government Services..."

Reallocation Report (the "Report") that proposed to reallocate the spectrum at issue in this proceeding, the National Telecommunications and Information Administration ("NTIA") recognized that radio astronomy constitutes such a unique, immensely important yet easily interfered with use of the spectrum, that those portions of the spectrum currently allocated exclusively to the Radio Astronomy Service ("RAS") should retain that exclusive allocation, and that the reallocation of neighboring frequency bands should be subject to conditions that restrict potential harm to radio astronomy. CORF strongly supports the proposals in the Report designed to protect users of the Radio Astronomy Service.

Radio astronomy is a vitally important tool used by scientists to study our universe. Through the use of radio astronomy, scientists have recently discovered the first planets outside the solar system, circling a distant pulsar. Measurements of radio spectral line emission have identified and characterized the birth sites of stars in our own Galaxy, and the complex distribution and evolution of galaxies in the Universe. Observations of supernovas witness the creation and distribution of heavy elements essential to the formation of planets like the

Earth, and of life itself. Furthermore, as noted in the Report, in addition to increasing knowledge of our world and the universe, radio astronomy has produced substantial benefits through the development of very-low-noise receivers and many other applications used in a variety of other radio applications.[4] In addition, the technique of very-long-baseline interferometry ("VLBI"), developed for cosmic observations, is increasingly producing substantial benefits through use in terrestrial observations, including measurements of global distances (e.g., identification of potential earthquake zones through measurement of fault motion), and through major contributions to navigation, including the tracking of spacecraft.[5] The continuing flow of benefits from radio astronomy, founded on years of work and substantial federal investment, must be protected.

As passive users of the spectrum, radio astronomers have no control over the frequencies that they need to study, or over the

[4] See Report at page 2-9 and "Views of the Committee on Radio Frequencies Concerning Frequency Allocations for the Passive Services at the 1992 World Administrative Radio Conference" (hereinafter, "Views of CORF"), attached hereto as Exhibit 1, at page 13.

[5] See, Views of CORF at page 13.

character of the "transmitted" signal. Furthermore, the emissions that radio astronomers detect are extremely weak--a typical radio telescope receives only about one-trillionth of a watt from even the strongest cosmic source. Radio astronomy is therefore particularly vulnerable to interference not only from licensed and unlicensed users in bands allocated to radio astronomy, but from spurious and out of band emissions from users of neighboring bands. Accordingly, if the benefits of radio astronomy are to be protected, wise spectrum management must be used. CORF believes that the recommendation made in the Report regarding restrictions placed on the use of the reallocated 2390-2400 MHz band are necessary for the protection of planetary research facilities at Arecibo, and thus urges the Commission to enact such restrictions.

II. Restrictions on the Use of the 2390-2400 and 2402-2417 MHz Bands Are Necessary to Protect Important Research Operations.

While radio astronomers are concerned about protecting the bands which are primarily allocated to RAS, they must also take great interest in other bands: due to the extreme sensitivity of radio astronomy receivers, radio astronomers are very vulnerable to the spurious emissions from services in bands next to the bands being reviewed. Such emissions can be as harmful to research as those from the same band.

As the Report recognized, the National Astronomy and Ionosphere Center performs important planetary radar research at 2380 MHz using the world's largest radio/radar telescope at Arecibo, Puerto Rico. Radar astronomy transmissions are conducted in a carefully controlled manner, with short-term transmissions from earth, which are detected as weak radar echoes from the objects reflecting them. Research from this facility has resulted in major contributions to knowledge of the solar system, including mapping of the surfaces of Venus and asteroids, and detection of orbital debris.

The proposal to reallocate the 2390-2400 MHz band, and to a lesser extent, the 2402-2417 MHz band, poses a substantial threat to these facilities. Accordingly, the Report proposed (at page 4-17), prohibiting airborne or space-to-earth links in the 2390-2400 MHz band, and placing limitations on terrestrial operations in Puerto Rico in the 2390-2400 MHz band. These restrictions (and as described below, restrictions on the 2402-2417 MHz band) are absolutely necessary to protect operations at Arecibo. Furthermore, while such restrictions would protect valuable planetary research operations, they are sufficiently limited, geographically and technologically, to allow for use in a wide variety of new terrestrial services.

III. The Commission Should Consider Limited Restrictions on Harmonic Emissions from Services in the 2402-2417 MHz Band.

Harmonic emissions from stations in the 2412-2418 MHz section of the 2402-2427 MHz band can interfere with the 4825-4835 MHz band, where the RAS has secondary status internationally and US footnote protection[6] in order to protect spectral line and continuum observations. Among the bands protected are ones used to find formaldehyde, which is an important constituent of the interstellar medium, and the 4.83 GHz and 14.5 GHz transitions are used to effectively determine the density of the emission region. Formaldehyde has been detected mostly in absorption within our Galaxy but recent studies at Arecibo have detected emissions in

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[6] Footnote US 203 says "Radio astronomy observations of the formaldehyde frequencies 4825-4835 MHz and 14.470-14.500 GHz may be made at certain radio astronomy observatories as indicated below: (list includes Arecibo Observatory). Every practicable effort will be made to avoid the assignments of frequencies to stations in the fixed or mobile services in these bands. Should such assignments result in harmful interference to these observations, the situation will be remedied to the extent practicable."

other prominent galaxies.[7] Formaldehyde emission from these galaxies reveal molecular gas in the very nucleus of the galaxy. Follow-up studies are in progress to study further these galaxies with the Very Large Array and further studies are planned with the Upgraded Arecibo.

The harmful interference threshold for astronomical observations in this particular band has been presented by ITU/CCIR Recommendation 769.[8] This threshold is -230 dB(W/m^2/Hz) for spectral line observations. These limits are rather stringent because radio astronomy observations are conducted with the largest possible telescopes and the lowest noise receiving systems in order to detect the extremely weak celestial signals.

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[7] A 1993 scientific publication reports on the detection of ten galaxies with anomalous formaldehyde emission. This type of emission is thought to be an indicator of activity in the nuclei of galaxies and provides a novel way to study the molecular gas in these spectacular galactic nuclei. Increased sensitivity of telescopes like Arecibo will undoubtedly enlarge the group of formaldehyde emitters and promote studies of cosmologically interesting and distant sources.

[8] ITU/CCIR Recommendation 769 describes in detail the harmful interference thresholds for radio astronomy observations in various observing bands. The thresholds have been determined assuming that an interfering signal should not introduce an error of more than 10 percent. The response of a radio telescope has been standardized to represent differently constructed telescopes.

CORF urges the Commission to consider the impact of second harmonic emissions during the selection of a service to occupy the 2402-2427 MHz in order to protect the 4830 MHz band. Considering that S-band transmission systems are less prone to harmonic emission than those at lower frequencies, a reduction of harmonic emissions below the harmful thresholds for RAS would not be an undue burden on the new occupants of the bands. CORF urges the Commission to consider these issues when selecting the services for this 2402-2417 MHz band and also urges the Commission to set strict standards to prevent transmitters in this band from producing signals above the harmful thresholds in the 4830 MHz band.

IV. Conclusion

That portion of the spectrum that is used by radio astronomers is a unique resource in that it has produced, and will continue to produce, remarkable cosmic discoveries, important information about our planet, and tangible technological benefits used in a variety of radio communications services. Yet, radio astronomers' use of this small fraction of the useable spectrum is uniquely susceptible to interference, and thus radio astronomy must be carefully guarded in the coming years. While CORF recognizes the Congressional imperatives that require the reallocation of certain portions of the spectrum, Congress, and the NTIA, also recognized the need to weigh the potential benefits of new spectrum-based services against the detrimental impact of such services on existing users. In the case of the 2390-2400 MHz band, the limited restrictions proposed in the Report will have little impact on any new terrestrial uses of that band, but will produce a substantial benefit of protecting valuable planetary research facilities in Arecibo, Puerto Rico. Similarly, limited restrictions on the 2402-2417 MHz band will also substantially benefit the work, and results, of radio astronomy. Therefore, in enacting rules for any new services using the 2390-2400 and 2402-2417 MHz bands, the Commission should include the limited restrictions proposed in the NTIA's Report, and herein.

Respectfully submitted,

NATIONAL ACADEMY OF SCIENCES'
COMMITTEE ON RADIO FREQUENCIES

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June 15, 1994

VIEWS OF THE COMMITTEE ON RADIO FREQUENCIES

CONCERNING FREQUENCY ALLOCATIONS FOR THE PASSIVE SERVICES AT THE 1992 WORLD ADMINISTRATIVE RADIO CONFERENCE

Committee on Radio Frequencies
Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES
Washington, D.C. · 1991

1994 reprinted

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Frank Press is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Robert M. White is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Samuel O. Thier is president of the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Frank Press and Dr. Robert M. White are chairman and vice chairman, respectively, of the National Research Council.

The Committee on Radio Frequencies acknowledges the assistance of the National Science Foundation and the National Aeronautics and Space Administration, whose continuing support of the committee has made this report possible.

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BOARD ON PHYSICS AND ASTRONOMY

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND APPLICATIONS

CONTENTS

I. INTRODUCTION

The scientific needs of radio astronomers and other users of the passive services for the allocation of frequencies were first stated at the World Administrative Radio Conference held in 1959 (WARC-59). At that time, the general pattern of a frequency-allocation scheme was

1. that the science of radio astronomy should be recognized as a service in the Radio Regulations of the International Telecommunication Union (ITU);

2. that a series of bands of frequencies should be set aside internationally for radio astronomy—these should lie at approximately every octave above 30 MHz and should have bandwidths of about 1 percent of the center frequency; and,

3. that special international protection should be afforded to the hydrogen line (1400-1427 MHz), the hydroxyl (OH) lines (1645-1675 MHz), and to the predicted deuterium line (322-329 MHz).

At the end of WARC-59, considerable action had been taken to meet these needs, and at subsequent conferences (with more limited tasks), the growing extent of the scientific needs has been stated and further steps taken to meet them.

The discovery of radio sources and the bulk of current knowledge about their nature and distribution, and of the processes responsible for the radio emission from them, have come through observations of the continuum radiation (continuous spectra) made at a limited number of frequencies at meter to centimeter wavelengths. Observations of intensity need to be made at a number of frequencies to determine the characteristic spectra of sources; but because the distribution of continuum radiation with frequency is relatively smooth, observations of this kind do not need to be made at specific or closely adjacent frequencies. Bands spaced at intervals of about an octave of the radio-frequency spectrum are normally satisfactory. However, some sources have spectral features requiring observation at closer spacings.

The bands made available to the Radio Astronomy Service, in accordance with the Final Acts of the World Administrative Radio Conference, Geneva, 1979, represent an improvement over the international allocations made to the Service in 1959, 1963, and 1971 and are a partial fulfillment of the requirements of the Service. However, many of the currently allocated bands have insufficient bandwidths; they are, in most cases, shared with active services; many apply to limited areas of the world; and there are large intervals between some of the allocated bands.

As the 1992 WARC approaches, the Committee on Radio Frequencies (CORF) restates in this document the views and needs of radio astronomers and remote sensing scientists for the protection of their research. There is a continuing need for review and updating of the allocations of frequencies for the passive services. The committee notes that with the discovery of new astronomical objects and the development of better equipment and techniques, passive radio scientists regularly use frequencies from the lowest allocated radio astronomy band at 13360-13410 kHz to bands above 500 GHz. The use of passive ground- and satellite-based instruments for meteorological and astronomical observation has further increased the need for more spectrum.

The needs for continuum observations when first stated in 1959 were based largely on the desire to measure the spectra of radio sources over a wide range of frequencies. Since that time, two developments have reinforced this need for continuum bands.

First, pulsars, which are rapidly rotating, highly magnetized neutron stars, have been discovered to be among the most exotic objects in the universe. The physics of pulsars involves the study of matter and radiation under the influence of extreme magnetic, electric, and gravitational fields. Pulsars now provide the most accurate timekeeping, surpassing the world's ensemble of atomic clocks for long-term time stability. They provide the best experimental tests of predictions of the theory of general relativity, the detection of gravitational radiation, and diagnostics of the interstellar medium's density and magnetic field. For these studies continuum bands, particularly those at frequencies below 3 GHz, are most valuable.

Second, the technique of very-long-baseline interferometry (VLBI) now allows radio astronomers and earth scientists to link radio telescopes many thousands of kilometers apart by recording on fast-running, high-density magnetic tape (using very stable oscillators as a reference) and to process the tapes to produce an interferometer system with several very long baselines. The technique of VLBI has proved invaluable in studying the structure of very distant radio sources and in monitoring crustal motions and rotational irregularities of the earth. For this technique to be fully exploited, telescopes in several different countries must observe together on exactly the same frequency. This is made much easier if the same passive frequency bands are protected in all of the regions of the world.

Since 1959 a large number of spectral lines from a wide variety of atoms and molecules in space have been discovered. The frequency range of radio astronomy now extends to at least 500 GHz. In particular the CO molecule, with frequencies at 115, 230, and 345 GHz and isotopes with frequencies at 110, 220, and 330 GHz, is critical to many aspects of astronomy. The opportunity to learn about the gas out of which stars are formed in our own and in distant galaxies depends considerably on access to all of these frequencies. The ground-state fine-structure line of atomic carbon at 492 GHz has been discovered and provides a truly unique opportunity for radio astronomy. However, the protection of spectral-line frequencies is a difficult task. In some simple cases, what is needed is clear; the value of H, OH, and CO line studies has grown, particularly as more sensitive instruments look farther out to objects with increasingly greater red shifts. This, in turn, has made it urgent to look for ways to extend the hydrogen- and hydroxyl-line protection below 1400 MHz, and similarly to extend the protected bands for the lines of OH and CO molecules. For many of the new molecular species, it is difficult to be precise as to their relative scientific importance. Thus continued review of the science, combined with protection of radio astronomy observations by footnote references to the Table of Frequency Allocation in the ITU Radio Regulations, is needed.

There are special difficulties for some spectral lines (the OH lines, for example), where radio emissions from airborne and spaceborne transmitters exist too close to the line frequencies. This difficulty is one that, in recent years, has grown greatly in importance, particularly with the introduction of higher-powered space transmitters and the use of spread spectrum modulation techniques. Because the radio astronomy and remote-sensing sensitivities are so great, and terrain shielding cannot be employed, it is most difficult to avoid interference from the sidebands of some spaceborne transmitters, even though their central transmitting frequencies may lie outside the radio astronomy bands.

As long ago as 1960, the vulnerability of radio astronomy to interference was being documented by the International Radio Consultative Committee (CCIR) of the ITU. Estimates of harmful thresholds for radio astronomy bands were published in CCIR Report 224-6. Thus it is now important to implement ways to protect radio-astronomy and other services from adjacent-band interference from air- and space-to-ground transmissions.

As it has in the past, CORF proposes that the bands allocated to the Radio Astronomy Service be afforded protection to the levels given in CCIR Report 224-6. Within these bands, the flux spectral density produced by services in other bands should not exceed these levels. The Radio Astronomy Service, in return, can claim no special privileges with respect to flux spectral density outside its bands except by mutual agreement with other services or by national arrangements.

The concept of a Lunar Quiet Zone has been studied and advanced as a valuable international resource for radio astronomers and for other scientists who are passive observers of the universe. The study of such a quiet zone has been undertaken within the CCIR and has resulted in CCIR Recommendation 479-3. Radio Regulations (RR29) numbers 2632 to 2635 define the shielded zone of the moon and prohibit harmful interference to radio astronomy except in Space Research and Earth Exploration Satellite bands. Work should continue on determination of appropriate protection of this zone.

The Radio Astronomy Service and the Earth Exploration Satellite Service (Passive) were considered at the 1979 WARC. Allocations to these services have allowed continuing useful research programs to be pursued. It is important that future radio conferences not change the Radio Regulations in ways that will be deleterious to these services. Although these services have additional needs, CORF is not pressing for new allocations or considerations at the 1992 WARC. However, the committee would welcome any changes in the regulations that required the use of better and more modern technical standards. CORF especially encourages the development of additional regulations to protect services from emissions spilling over from adjacent bands.

II. SCIENTIFIC BACKGROUND

Radio Astronomy

The fact that radio waves can be received on the earth from celestial objects was first discovered by Karl Jansky of the Bell Telephone Laboratories in 1932, as a by-product of studies of noise in radio-communication systems. Since that time, the science of radio astronomy has expanded to the point that many types of astronomical objects have been studied by radio methods, and many important discoveries have been made.

Whereas the light waves studied by optical astronomers come from hot objects such as stars, celestial radio waves come mainly from cooler objects, such as the gas between the stars, or from electrons in ordered motion. Radio astronomers study many of the same celestial objects that optical astronomers do, and, in addition, their work has revealed new classes of objects and quite unexpected forms of activity. Astronomical studies provide a laboratory in which matter can be seen over a wide range of physical conditions, the extremes of which cannot now or in the foreseeable future be reproduced on the earth. Extremes of density, temperature, and pressure and unusual chemical compositions can all be found at various places in the universe and are under close study by astronomers.

Some of the sources of radio waves are believed to be at the farthest limits of the known universe. Because these sources are so far away, the radio waves have been traveling for many billions of years, thereby providing information about the condition of the universe a very long time ago. Closer to home, there are large sections of our Milky Way Galaxy that cannot be seen by optical astronomers because light waves are stopped by clouds of interstellar dust; radio waves can penetrate these dust clouds, enabling us to study the whole of our galaxy and other nearby galaxies.

The spectrum of the celestial radio waves reaching the earth contains a broad continuum that covers the whole range of frequencies that can penetrate the earth's atmosphere, together with a large number of atomic and molecular spectral lines, each of which is confined to a narrow frequency range.

The radio continuum arises from two principal mechanisms: (1) thermal emission, the intensity of which is proportional to the temperature, produced in an ionized gas of unbound electrons and protons; and (2) nonthermal emission, mostly produced by the synchrotron process, in which very-high-speed electrons spiral around magnetic-field lines. This mechanism is found in the disks of normal galaxies, in the remnants of supernova explosions, and in unusual types of galaxies known as radio galaxies and quasars.

Spectral line radiation is emitted when an atom or molecule gains or loses a discreet amount of energy. This radiation has a specific frequency and wavelength and thus results in a line in the radio spectrum. Each type of atom and molecule has its own unique set of lines. Widely observed spectral lines occur at a frequency near 1420 MHz, arising from neutral (nonionized) hydrogen atoms in the interstellar gas, and at frequencies of 115 and 230 GHz, arising from carbon monoxide molecules. Other spectral lines have been detected from several atomic species and from a large number of molecules found in space and in planetary and stellar atmospheres.

In the solar system, the sun has always been an important object for study by radio astronomers. The slowly varying component of solar radio emission has been found to provide one of the best indicators of the variation of solar activity over the sun's 11-year cycle. In addition, the intense and rapid bursts of solar radio emission are providing greater understanding of what happens on the sun during active periods and the way the sun influences events in the earth's atmosphere, near-earth space, and other portions of the solar system.

The planet Jupiter also produces frequent bursts of radio waves, and it was the study of these by radio astronomers that first showed the coupling between Jupiter's magnetosphere and the satellite Io. This has been confirmed and extended by measurements in the vicinity of Jupiter from the Pioneer and Voyager spacecrafts.

Radio astronomy has provided new information about the early and late stages of the lives of stars, stages that are important in the evolutionary process but that are not well understood. Strong and localized sources of radiation in spectral lines of the hydroxyl and water molecules are found in the shells of objects that appear to be in the process of becoming stars. Some compact sources of thermal continuum radiation, which are embedded in dense clouds of dust, also seem to be protostellar objects. Recently, giant breeding grounds of massive new stars, and dark clouds where stars similar to the sun are born, have been detected. Millimeter and submillimeter radio telescopes and interferometers are expected to lead astronomers to a new era of understanding of the star formation process.

At the other end of the stellar life cycle, radio astronomers study supernova remnants, the material blown out from massive stars in giant explosions at the end of their lives as stars. Radio astronomers have also discovered numerous very dense and compact neutron stars, which are the remnants of supernova explosions. A rapidly rotating neutron star often is observed as a pulsar, a periodic radio source, which emits a narrow beam of coherent radiation as the neutron star rotates. The period of some pulsars is of the order of a millisecond, making these objects the most stable clocks known.

Spectral lines have now been detected from about 80 different molecules in interstellar space. Many of these are organic molecules, and some are quite complex. These discoveries have raised interesting questions about how complex molecules have been built up and how further development might lead to the precursors of life, as a possibly widespread phenomenon in our galaxy and the wider universe. Astronomers, who study astrochemistry, attempt to trace out the development of a chain of chemical compounds by searching for the appropriate spectral lines. To study the physical conditions inside a molecular cloud, or in different portions of the cloud, it is necessary to compare the relative strengths of lines from different molecules, or of different transitions (lines) from the same molecule. In some cases, a set of lines of a particular type of molecule, involving different isotopes of one or more of the constituent atoms (hydrogen, carbon, nitrogen, or oxygen), can be studied; these studies can give valuable information on the relative densities of the various isotopes in the interstellar medium, and thus indirectly on the general evolution of the chemical elements.

Studies of some spectral lines are more important than others because the atoms or molecules concerned occur in greater numbers, the transitions are more easily excited, or they are particularly good for indicating the conditions inside a cloud or the location of the spiral arms in a galaxy. However, to understand the chemical and physical conditions properly, it is necessary to intercompare a large number of lines.

Studies of galaxies depend heavily on observations of spectral lines at radio wavelengths. These observations provide information on the kinematics of the gas in the galaxies and on the abundance of the elements making up that gas. The hydrogen line has been used to learn about the gravitational potential of the galaxies, leading to the realization that a substantial fraction of the masses of galaxies is made up of material that is not visible. This is called the "missing mass" problem and is vital information in deciding whether the universe will expand forever or will eventually collapse on itself. Further, the hydrogen spectra of galaxies is used for determining their distances and therefore helping to establish the large-scale structure of the universe.

Many distant galaxies are unusually strong continuum emitters of radio waves but are relatively faint when viewed with an optical telescope. These "radio galaxies" are the subject of many investigations attempting to discover the source of their radio energy and the circumstances of the explosive events that seem to have occurred in many of them.

The most powerful radio sources known are quasars, which are distant, compact objects that emit radio energy at a prodigious rate. A quasar is believed to be the nucleus of a galaxy that is usually too distant for anything but the central core to be seen. The study of quasars involves fundamental physics, in the continuing attempt to understand their sources of energy. The nuclei of some other classes of galaxies show great activity and unusual energy production. Even the nucleus of our own galaxy is a small-scale version of an active nucleus and can best be studied by radio methods.

Remote Sensing of the Earth

Observations of the earth's atmosphere, land areas, and oceans in the radio part of the electromagnetic spectrum have become increasingly important in understanding the earth as a system. Currently operational satellite instruments, including the Microwave Sounding Unit (MSU) and instruments on the U.S. Air Force's passive microwave weather satellites (SSM/I and SSM/T) provide key meteorological data sets. Future remote-sensing satellite missions such as NASA's Earth Observing System (EOS) and the Tropical Rainfall Measurement Mission (TRMM) are currently under planning. The missions are expected to improve measurements of atmospheric temperature, water vapor and precipitation, soil moisture, concentrations of ozone and other trace gases, and sea surface temperature and salinity. These multiyear, multibillion-dollar missions are international in scope, reflecting the interests of many countries in obtaining accurate meteorological, hydrological, and oceanographic data, and measurements of land surface features and trace gases in the atmosphere.

The outcome of such remote sensing missions will be improvements in weather forecasting; severe storm monitoring; water resource, land, and biota management; and improved global climate and atmospheric chemistry models. The long-term economic impact of the information from remote sensing satellites promises to be substantial, in both the production of food and other agricultural products and the operation of businesses and industries that are dependent on both local weather and long-term climate stability. A substantial number of lives can be saved through advanced warning of dangerously inclement weather. The remotely sensed information will also be used to provide scientifically based guidelines for environmental policy.

Passive Sensors

A major component of earth remote sensing systems consists of spaceborne passive microwave radiometers. These sensors are similar in their basic design and sensitivity to radioastronomy receivers and are essential to the overall success of satellite-based earth remote sensing missions, due to their ability to probe through optically thick clouds. This unique feature of passive microwave sensing complements the capabilities of infrared and optical sensors.

As in radioastronomy, bands near certain atmospheric spectral lines and transmission windows are required for passive earth exploration satellites. Several bands, listed in Tables 1 and 2, have been identified and investigated for their particular capabilities. Atmospheric temperature profiles can be measured using channels near O_2 absorption lines at 50-70 GHz (within the 5-mm absorption band) and at 118 GHz. Water vapor profiles can be measured using channels near H_2O absorption lines at 22.235 and 183.310 GHz, and potentially at 325 GHz. Precipitation exhibits no narrow spectral features and thus requires a widely spaced set of channels for observation. Useful channels are near 6, 10, 18, 37, 90, 157, and (potentially) 220 and 340 GHz.[1] Soil moisture measurement requires a low-frequency microwave channel near 1 to 3 GHz. Sea surface temperature and wind speed measurements require channels at slightly higher frequencies, near 6, 10, and 18 GHz. Concentrations of atmospheric trace gases (e.g., ozone) can be measured by observing atmospheric radio emissions near molecular resonances.

The required sensitivities for retrieval of geophysical parameters are listed in Table 1, in terms of the required accuracy of the brightness temperature values, which range from 0.1 to 1.0 K. In order to obtain these sensitivities, wide bandwidths (from 60 MHz to 6 GHz) are required. The particular bandwidth requirement depends on the use of the channel, the receiver sensitivity, and the observation time; minimum acceptable bandwidths are given in Table 1. The listed bands are consistent with CCIR Recommendation 515, "Frequency Bands and Performance Requirements for Satellite Passive Sensing," although wider bandwidths are suggested for some frequencies.

In order to obtain the sensitivity required for earth remote sensing, interference from radio sources must be kept below the thresholds described in CCIR Report 694. The current allocations for passive earth exploration satellites were made during the 1979 WARC.

Active Sensors

Another critical component of current and planned earth remote sensing systems consists of active spaceborne sensors, such as synthetic aperture radars (SARs), radar altimeters, and precipitation radars. Uses of active sensors include measurement of soil moisture, snow, ice, rain, clouds, atmospheric pressure, and ocean wave parameters, and mapping of geologic and geodetic features and vegetation.

Suggested channels for active earth remote sensing are 100-MHz-wide frequency bands near 1, 3, 5, 10, 14, 17, 35, and 76 GHz. Wider bandwidths (up to 600 MHz) are required for altimeter measurements with vertical resolution less than 50 cm. These bands are consistent with CCIR Recommendation 577-1, "Preferred Frequency Bands for Active Sensing Measurements." The current allocations for active earth remote sensing were made during the 1979 WARC.

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[1]The High Resolution Multifrequency Microwave Radiometer, part of NASA's planned Earth Observing System (EOS), includes the Advanced Microwave Sounding Unit, which will provide atmospheric soundings of temperature and water vapor using channels in the oxygen resonance band (50-60 GHz) and the water vapor line at 183 GHz; the Advanced Mechanically Scanned Radar, a microwave imager operating at 6, 10, 18, 21, 37, and 90 GHz; and the Electronically Scanned Thinned Array Radiometer, an imaging radiometer that operates at 1.43 GHz.